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Monitoring white whales (*Delphinapterus leucas*) with echolocation loggers

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Abstract Monitoring programmes for white whales (*Delphinapterus leucas*) have been called for repeatedly in recent years because this species is likely to be negatively impacted by climate change, but also because such a broadly dispersed, high trophic feeder can serve as an effective ecosystem sentinel. Arctic ecosystems are difficult to monitor because of the extensive winter ice coverage and extreme environmental conditions in addition to low human population densities. However, passive acoustic monitoring has proved to be a reliable method to remotely survey the presence of some marine mammals in the Arctic. In this study, we evaluate the potential use of echolocation loggers (T-POD and C-POD, Chelonia Ltd.) for remote monitoring of white whales. Captive experiments and open water surveys in three arctic/subarctic habitats (ice-noise-dominated environment, ice-free environment and low-turbidity waters) were used to document detection performance and to explore the use of logger angle and inter-click interval data to look at activity patterns and tidal influences on space use. When acoustic results were compared to concurrent visual observations, echolocation detection was only attributed to periods of white whale presence near the recorder deployment sites.

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Both T-PODs and C-PODs effectively detected echolocation, even under noisy ice. Diel and tidal behavioural patterns were identified. Acoustically identified movement patterns between sites were visually confirmed. This study demonstrates the feasibility of monitoring white whales using echolocation loggers and describes some important features of their behaviour as examples of the potential application of this passive acoustic monitoring method in Arctic and subarctic regions.

Keywords Beluga whales · *Delphinapterus leucas* · Echolocation loggers · Passive acoustic monitoring · T-POD · C-POD

Introduction

Monitoring of white whales has been called for repeatedly in recent years because this species is likely to be negatively impacted by climate change, but also because such a broadly dispersed, high trophic feeder can serve as an effective sentinel for the ecosystem(s) in which it lives (Moore 2008; Moore and Huntington 2008; Simpkins et al. 2009; Bossart 2011; Gill et al. 2011). Developing cost-effective monitoring techniques for such species should be considered a top priority. Arctic ecosystems are difficult to monitor because of the extensive winter ice coverage and extreme environmental conditions (including both darkness and cold). Ship-based marine mammal surveys are extremely expensive, and they become logistically challenging outside the summer season. However, passive acoustic monitoring with bottom-mounted audio recording packages has proved to be a reliable method to remotely survey the presence of some marine mammals in the Arctic (Blackwell et al. 2007; Delarue et al. 2009; Simon et al. 2010a; Moore et al. 2012); this technology has been utilized mainly for baleen whales. Detecting odontocete vocalizations, which are higher frequency, requires digitizing at higher sampling rates, more power and greater memory storage, all of which compromise the cost and running time of recording packages. An alternative technique for remote acoustic monitoring of odontocetes is selective echolocation logging which incorporates signal processing to store only data useful in the detection of click trains. However, detection efficiency for this type of recording relies on previous knowledge of the acoustic characteristics of the echolocation signals. Such loggers have been mainly developed for harbour porpoise (*Phocoena phocoena*) detection and they have been modified to detect bottlenose dolphins (*Tursiops truncatus*) as well; echolocation signals have been thoroughly described in both of these species (e.g. Au 1993). However, few other odontocete species have been acoustically monitored with echolocation loggers, mainly because echolocation signals have not been characterised for them. This is not the case for echolocation behaviour of white whales, which has been relatively well studied (e.g. Au et al. 1985, 1987; Penner et al. 1986; Turl and Penner 1989; Turl et al. 1991; Rutenko and Vishnyakov 2006; Lammers and Castellote 2009), but surprisingly, acoustic monitoring by means of echolocation loggers has never been attempted for this species. Passive acoustic monitoring is capable of producing relative information on distribution range as well as accurate information on habitat use and potentially on trends in distribution and population abundance of odontocetes, at low cost, using consistent, automated methods.

Seasonal presence patterns and habitat use are key features for the design of effective white whale management and conservation plans; however, these data are often difficult to obtain. Passive acoustic monitoring might offer a cost-effective means to gather such data for white whales and thus may represent a real advancement in remote monitoring of this sentinel species in the Arctic ecosystem. This study evaluates the potential of Timing POrpoise Detectors (T-PODs) and a newer version of this technology that incorporates digital signal processing characteristics, the Cetacean and POrpoise Detectors (C-PODs) (Chelonia Ltd., UK) for white whale monitoring. Both captive experiments and open water surveys in three arctic/subarctic habitats were undertaken in order to: (1) describe the echolocation click energy distribution of white whales for on- and off-axis clicks; (2) evaluate T-POD white whale echolocation detection performance in captivity; (3) validate the detection of white whale echolocation clicks in different habitats (ice-noise-dominated environment, ice-free environment and low-turbidity waters), using T-PODs and C-PODs and (4) validate the use of logger angle and inter-click interval (ICI) data to describe temporal activity patterns as an indication of habitat use and specific behaviour patterns.

Materials and methods

Experiments in captivity

Description of the echolocation click energy distribution of freely moving white whales

Most of the current knowledge regarding echolocation characteristics for white whales comes from experimental studies where the animals were stationary, with support from either a hoop or a bite plate, or both (e.g. Au et al. 1985, 1987, Turl and Penner 1989; Turl et al. 1991; Lammers and Castellote 2009) to maintain a constant distance and angle of incidence to the hydrophone. For this study, there was a need to describe the spectral characteristics of echolocation signals recorded at variable distances and angles of incidence, as would occur in recordings of free-ranging white whales passing through the detection range of a deployed instrument. Experiments were performed at L'Oceanogràfic of the City of Arts and Sciences (LOCAS) of Valencia, Spain, in 2006. The aquarium hosted two adult white whales: a 15-year-old male and a 9-year-old female. The white whale exhibit at this facility was made up of four interconnected pools. The pool surfaces were concrete, covered by epoxy, which were created to imitate the look of an icy environment. The size of the facilities and irregular wall shape created a relatively free-field environment with limited interfering acoustic reflections from the sides of the pool.

Echolocation clicks were recorded using a broadband system with 0–180 kHz flat frequency response (±3 dB), sampling at a rate of 380 kHz, composed of a single omnidirectional hydrophone (Brüel and Kjaer model 8103), with a conditioner amplifier (Brüel and Kjaer model 2692-OS1) that had high-pass (80 dB/decade) and low-pass (40 dB/decade) filters set to 10 Hz and 180 kHz, respectively, and a 16-bit data acquisition board (National Instruments model USB6251) connected to a laptop computer, while both whales swam freely in their facilities. The hydrophone was installed at a depth of 2.5 m and protected by plastic tubing. Received sound pressure level in dB re1μPa rms was calculated for the total duration of each recorded click train with a frequency resolution of 1 kHz for the range 10–180 kHz. The resulting sound power spectra were averaged from 979 click trains to obtain a composite of the echolocation click energy distribution. The composite values and 1× standard deviation as well as the background noise levels were plotted as a line diagram.

Echolocation loggers

Two types of echolocation loggers were used in this study, T-PODs and C-PODs. The T-POD was designed to detect harbour porpoise clicks, taking advantage of the narrow bandwidth of these clicks. Clicks are registered as being detected when the ratio of the output of a predefined target frequency to the output of a predefined reference frequency exceeds a value set by the user. Different target and reference frequency configurations can be set for successive 10 s time periods ('scans') within each minute. The automated click train detection function in the T-POD.exe program filters out random clicks from background noise, resulting in files containing only clicks that occur in sequences ('trains'), which can include both cetacean and boat sonar sources (depth sounders, etc.). Todd et al. (2009) provide a description of the T-POD hardware and of the processes of data collection and classification; numerous studies have reviewed settings and T-POD functionality (e.g. Thomsen et al. 2005; Philpott et al. 2007; Kyhn et al. 2008; Simon et al. 2010b).

C-PODs are an upgraded digital development of the T-POD that became commercially available while this study was underway. The C-POD uses a 12-bit analogue to digital converter to read the amplitude of pulsive signals, derives the frequency and bandwidth from analysis of zero-crossing times and logs the time, dominant frequency, sound pressure level, duration and bandwidth of each pulsive event. Events are selected if sufficiently tonal and loud and include many non-cetacean sources that are rejected during the post-processing train detection. The train detection and classification carried out during automated post-processing of these data is enhanced by the richer data set, compared to the T-POD which uses only time and duration of clicks. Another major difference between T-PODs and C-PODs is that the latter requires minimal setting decisions by the user. Reference and target frequencies are no longer defined for the signal scanning process, and therefore, an experimental set-up such as the one described here for T-PODs to test settings performance is not necessary.

Evaluation of the performance of T-POD settings for white whale echolocation detection

One T-POD (version 5) was tested at the LOCAS facilities. The T-POD target and reference frequency filter band settings used for white whale detections subsequently in the wild were based on the composite results from echolocation recordings performed at LOCAS (presented below). Due to the documented differences in spectral energy distribution of white whale echolocation signals with changing click rate, distance to target and angle of incidence (e.g. Au et al. 1987), these target and reference frequency settings needed to be tested to determine differences in the detection efficiency of T-PODs. The instrument was deployed 12 times at the white whale facilities at LOCAS for periods of 24 h at a depth of 1 m, attached to a gate separating two pools. For each deployment, target and reference frequency settings were changed. Tested scan settings are summarized in Table 1. Since 6 different target and reference frequency settings were tested, the deployment schedule included 6 consecutive deployments with the T-POD set to scan a single frequency range in each deployment (a continuous scan of a constant frequency range). In order to avoid detection bias due to changes in behaviour of the whales between deployments, a series of another 6 deployments were conducted; during the second set of deployments, the T-POD was set to scan each of the 6 frequency ranges consecutively (6 different frequency ranges scanned one after the other in a looped cycle). Results from both types of deployments were compared. Logged data were analyzed using T-POD associated software (Version 8.24; train filter Version 4.1; www.chelonia.co.uk). Only clicks classified as "Cet all" by the T-POD software were included in this analysis. These are trains with the two lowest levels (out of four) of "false positive" cetacean detections; the four levels are determined by the post-processing software and correspond to differing positions along a receiver operating characteristic curve for the detector (see Thomsen et al. 2005 for an explanation of classifications). Total number of detection-positive minutes (minutes in which at least one echolocation click train was detected, DPM) for each target frequency used in the 24-h deployment period was calculated, and the median number of DPM from all 6 deployments was used to compare results between scanned frequency bands.

Previous studies identified differences in sensitivity and hence detection thresholds between individual T-PODs (see Kyhn et al. 2008). In order to assess whether calibration of multiple T-PODs used in the field for this study would be necessary, four time-synchronized units were simultaneously deployed, attached to each other, for three periods of 24 h in the white whale facilities at LOCAS. Differences in detection-positive hours throughout the three 24-h periods across all T-PODs were smaller than 2 %; it was therefore assumed that differences in detection thresholds were small enough to allow direct comparison of data among instruments.

Open water study areas

In order to test the detection efficiency of T-PODs for white whale echolocation clicks with the settings defined by the LOCAS experiments, surveys were organized in three arctic/subarctic regions. These had different white whale populations, environmental characteristics and acoustic properties of the environment.

Kongfjorden, Svalbard, Norway

The first survey was organized in Kongfjorden, located on the northwest coast of Spitsbergen, Norway in the Svalbard Archipelago, in May 2007 (79°N 12°E). Kongfjorden is open to the West Spitsbergen Shelf and is subject to intermittent exchange between turbid glacial-fjord waters and clear offshore Atlantic waters. However, during the winter of 2005–2006, there was a major inflow of Atlantic Water that resulted in this fjord remaining free of sea ice (Cottier et al. 2007), a situation that has continued through to the present (Norwegian Polar Institute, unpubl data). This area has low-turbidity conditions in spring, when the T-PODs were deployed, because the air temperature is low and the input of melt-water has not yet started (Hanelt et al. 2001).

White whales are the most commonly observed and most numerous cetaceans in the Svalbard Archipelago (Lydersen et al. 2001); however, the population size is unknown.

Disenchantment Bay, Alaska

The second survey took place in Disenchantment Bay (60°N 139°W) located along the south-central coast of Alaska, USA, in May 2008. Water turbidity is extreme in

Table 1 T-POD scanned frequency ranges, scan settings and analysis settings from LOCAS white whale facilities and the three field study area

Instrument type	T-POD	T-POD	T-POD	C-POD	T-POD
Location	Experiments in captivity	Kongfjorden, Svalbard, Norway	Disenchantment Bay, Yakutat, Alaska, USA	Disenchantment Bay, Yakutat, Alaska, USA	Cape Beluzy, Solovetskiy Island, White Sea, Russia
Frequency range (target/reference) in kHz	50/30, 56/92, 70/92, 70/113, 70/130 and 92/130	36/16, 41/16, 50/22, 50/30, 70/113 and 70/130	70/113 and 50/30	20–160 kHz	70/113 and 50/30
Scanning type[a]	Consecutive	Consecutive and dual	Dual	–	Dual
Logging type	Continuous	Continuous	Continuous	Continuous	Continuous
Number of clicks logged per scan	Unlimited	Unlimited	Unlimited	Unlimited	Unlimited
Click bandwidth	5	5	5	–	5
Noise adaptation	+	+	++	–	++
Sensitivity	6	6	10	–	10
Click train quality	Cet all	Cet all	Cet all	Cet hi, Mod and Lo	Cet all
Minimum click duration	0	0	>10 µs	0	0

[a] Consecutive logging refers to consecutive scans at different frequency ranges. Dual logging refers to alternate scans at two different frequency ranges

this study area. Disenchantment Bay has annual sediment accumulation rates of several to tens of metres because of the presence of several glaciers, including Hubbard Glacier which is the longest tidewater glacier in North America (Willems et al. 2011) and the largest non-polar tidewater glacier in the world (Ritchie et al. 2008). This glacier front has a major effect on the presence of rafting icebergs, bergy bits and growlers in the study area (Cowan et al. 1997). Calving can remove large amounts of ice from glaciers in very short times, and during this field study, the amount of ice in the study area fluctuated from 0 to 100 % sea surface coverage over periods of a few hours. The combination of wind, currents and tides (that retrieved or stranded icebergs) made the presence of drifting ice extremely unpredictable and dynamic.

The presence of white whales in Disenchantment Bay is intriguing. Small groups of white whales have been sporadically documented in this region since 1976 with group size estimates ranging from 2 to 21 whales (see Laidre et al. 2000). Genetic results suggest that these are not likely random whales travelling from the Cook Inlet population, but rather a small resident population that might have a unique ecology and a restricted seasonal home range (O'Corry-Crowe et al. 2006).

White Sea, Russia

The third survey took place in Cape Beluzy (65°N 36°E), located on the west coast of Solovetskiy Island, White Sea, Russia, in July 2008. In July, no ice is present in the White Sea, and turbid waters reach the study area from the Onega delta area (Filatov et al. 2005). Along-shore cyclonic circulation in the White Sea directs the flow of relatively transparent Barents Sea waters along the western White Sea coast, reaching as far as Solovetskiy Island (Kopelevich et al. 2004). Therefore, turbidity in the study area was not as extreme as the conditions observed in Disenchantment Bay but waters were not as clear as in Kongfjorden.

White whales inhabit the White Sea year-round, although they are more regularly observed from the end of May to September (Matishov and Ognetov 2011). The population size estimate for resident White Sea white whales is 2,000–2,500 whales (Bel'kovich 2004), with unknown proportions of resident and migratory animals. Cape Beluzy has been identified as a gathering area (Bel'kovich et al. 2002).

Survey protocol

The survey protocol was similar in all three study areas and is summarized in Table 2. Concurrent visual observations were made from land in all T-POD and C-POD deployments. Deployment periods varied from few hours to 18 days, depending on how many times the instruments were serviced to test different detection settings.

Validation of click spectra recorded at LOCAS

In order to explore the click energy distribution and click rate, echolocation clicks were recorded from a drifting boat in the vicinity of white whales in Krossfjorden on 15 May 2007 using an omni-directional hydrophone (Brüel and Kjaer model 8103), a Reson amplifier model VP-2000 with bandpass filters set to 500 Hz and 500 kHz and a TiePie Engineering (Netherlands) 12bit USB oscilloscope model SH3 with a sampling rate of 1 MHz connected to a laptop computer. The system had a 2–130 kHz flat frequency response (±3 dB). The hydrophone was deployed at 1.5 m depth.

Two C-PODs (version 0) were deployed at various locations in Disenchantment Bay, Alaska, in May 2009 but one of the two C-PODs was lost when it became entangled with drifting ice. C-PODs were deployed at depths varying from 5 to 15 m with concurrent visual observations during a period of 7 days. Observers noted presence and absence data, general surface behaviour, group size and group composition. C-PODs were set to log continuously using a 20-kHz high-pass filter with an unlimited number of clicks logged per minute. The peak frequency of each click was plotted as a histogram to investigate click energy distribution. C-POD data were analyzed with C-POD.exe version 2.16 (KERNO classifier version 2.016). C-POD.exe default settings were used for the analysis (Hi and Mod train quality, all cetacean species, unmodified train values and click filters) with the addition of Lo train quality level to explore the risk of accepting false detections.

Deployment and collection of T-POD data

Two T-PODs (version 5) were moored daily at a depth of 1–3 m, attached to an abandoned pier structure near the Ny-Ålesund research station (Kongfjorden, Svalbard). Concurrent visual observations overlooking the deployment site were carried out for a total of 41 h over a period of 10 days in May 2007; presence and absence data, general surface behaviour, group size and group composition of white whales were collected. Both units were retrieved and redeployed daily so that data could be downloaded and scanning settings modified. Tested settings are summarized in Table 1. Train quality level 'Cet all' was applied in the T-POD software to analyze acoustic detections.

Four time-synchronized T-PODs (version 5) were deployed at a number of near-shore locations at depths between 5 and 15 m in Disenchantment Bay for a period of 10 days in May 2008. A mooring system without a surface buoy was designed, based on local fishing practices.

Table 2 Field work survey protocols for all three study areas where echolocation loggers were tested

Study area	No. of instruments and type deployed	Deployment periods	Deployment sites and type	Observation sites and type	Other acoustic sampling
Kongfjorden, Svalbard, Norway	2 T-POD v5	24 h	2 Old pier attachment	1 Focal sampling	Dipping hydrophone recordings
Disenchantment Bay, Yakutat, Alaska, USA	4 T-PODs v5 and 2 C-PODs v0	24 h to 5 days	5 Mooring with sinking line	2 Focal sampling	Dipping hydrophone recordings
Cape Beluzy, Solovetskiy Island, White Sea, Russia	1 T-POD v5	18 days	1 Standard mooring with buoy	1 Focal and scan sampling	None

A sinking 9-mm line, designed for longline fishing, was attached to the moored system from shore, where it was attached to a buoy and secured with a 7.5 kg Danforth anchor on the beach. The buoy acted as a land mark for the deployment location and was used to recover the T-POD and mooring system. Scan settings are summarized in Table 1. Both ‘Cet all’ (click trains classified as having a high and low probability of being of cetacean origin) and Cet hi’ (click trains classified as having a high probability of being of cetacean origin) click train quality levels were applied in the analysis of acoustic detections. Additionally, the minimum duration of clicks to be included in the analysis was increased from 0 to 10 µs. The presence and absence of false detections, at the two different train quality levels applied in the analysis, was compared for the periods when both acoustic and visual monitoring was conducted. This conservative analysis approach was adopted because of prevailing noise from ice in this environment. Tidewater glacier calving activity, as near as 200 m from deployment sites, concentrated a massive amount of drifting ice pieces of various sizes in the study area. All of the ice gradually melted or drifted away via the effects of wind and tidal currents, but deployment sites remained densely covered in ice for hours every day. These ice conditions resulted in an extremely noisy recording environment (see results). Concurrent visual observations were carried out from two stations, allowing visual coverage of all deployment sites; presence and absence data, general surface behaviour, group size and group composition were collected (see Fig. 1).

One T-POD (version 5) was deployed off Cape Beluzy at a depth of 3–5 m, using a standard configuration mooring line (including an anchor and surface float), for a period of 18 days in July 2008. Scan settings for these deployments are summarized in Table 1. Both ‘Cet all’ and ‘Cet hi’ click train quality levels were compared in the analysis. Concurrent visual observations were made daily (both during daytime and low light periods) from an observation tower to obtain presence and absence data, general surface behaviour, group size and group composition.

Validation of T-POD and C-POD data: visual and acoustic comparison of white whale detections

Concurrent visual observations with both T-POD and C-POD deployments allowed for a direct comparison of acoustic data and visually assessed presence and absence of white whales in all study areas. T-POD and C-POD data were analyzed, using the analysis settings summarized in Table 1, to obtain all the DPMs that occurred within the periods of visual observation effort for each deployment site in all study areas. Initial and final times for each visual encounter were used to validate (acoustic detection occurred within a period of visual presence of white whales in the deployment site) or to reject (acoustic detection occurred within a period in which white whales were not observed) every DPM.

White whale presence and diel patterns

Since the duration of the deployments was not 24 h for all sampled days in all study areas (e.g. first and last day, moorings recovered to change scanning settings and later redeployed, etc.), the percentage of DPM per day for each deployment site was calculated in order to compare white whale presence between deployment sites within and between study areas. The average number of DPM (±SE) for each hour of the day was calculated in Disenchantment Bay and Cape Beluzy for each deployment site to identify potential diel patterns in white whale presence or echolocation behaviour. To test for differences in the average DPM per hour, an ANOVA was calculated with average DPM as the independent variable and hour as the dependent variable. The Kongfjorden data set was omitted from this analysis because there were too few detections to analyze potential diel patterns.

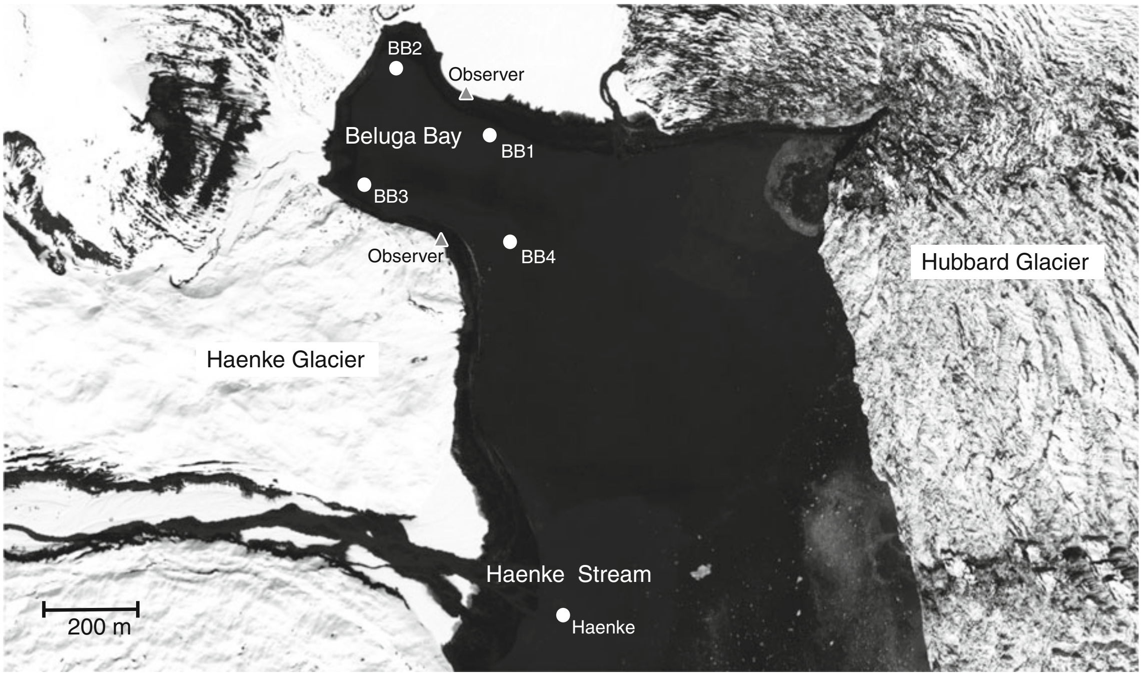


Fig. 1 Aerial view of the study area in upper Disenchantment Bay, Alaska. Deployment sites are indicated with *circles* and observer stations with *triangles*

Movement patterns

Movement patterns were only analyzed in Disenchantment Bay because this was the only study area that included several concurrent visual and acoustic monitoring stations. Acoustic detection periods were compared to visual sighting periods at each deployment site, and the sequence in which detections occurred at different sites was used to identify the direction of movement of the whales. Visual interpretation of white whale movements was used to validate the interpretation of acoustic data.

Relationship between tidal cycles and the presence of white whales

T-PODs log the longitudinal orientation of the instrument with a tilt sensor that was designed to be used as an on/off angle switch, allowing the user to control the beginning of logging activity during deployment or, when deployed within an intertidal zone, to automatically switch the instrument to stand-by mode during low tide periods. T-PODs log the deviation from vertical position (within 1 degree resolution) once per minute. This feature allows T-PODs to indirectly collect a rough estimate of current flow if the mooring design is sensitive to currents; however, to our knowledge, this application has not yet been tested. The mooring design in Disenchantment Bay and Cape Beluzy allowed the T-POD's orientation to change with tidal flow since the instrument was positively buoyant and was attached to the anchor line from a single point located at the lower end of the housing. Thus, the tidal cycle was monitored via the T-POD's angle sensor. Tide data obtained from tide tables from nearby locations were compared to T-POD angle data in Disenchantment Bay and Cape Beluzy. Correlation between T-POD angle and the number of detected echolocation clicks per minute was analyzed for all deployment locations in these two study areas to explore the relationship between the tide cycle and the presence of white whales. Pearson Correlation analysis was used for number of detected echolocation clicks per minute and CPOD angle.

The data collected in Kongfjorden were too scarce for this type of analysis.

Foraging behaviour

Time intervals between clicks within echolocation click trains, termed inter-click intervals (ICI), have been used as a behavioural indicator in porpoises (e.g. DeRuiter et al. 2009; Verfuss et al. 2009), beaked whales (e.g. Johnson et al. 2004), sperm whales (e.g. Miller et al. 2004), and to a certain extent in narwhals (Miller et al. 2005) and white whales (Roy et al. 2010). Certain click train temporal patterns can be associated with foraging behaviour (Verfuss et al. 2009). In order to explore potential temporal or spatial ICI patterns in white whale detections from Disenchantment Bay and Cape Beluzy, the percentage of buzzes over all clicks detected, defined as fast click trains containing clicks with a minimum ICI <2 ms, was calculated for all deployment locations, and mean and SE values for minimum ICI of click trains grouped by time of day were calculated. Differences between hours were analyzed with one-way ANOVA. The threshold of 2 ms was selected as a conservative threshold according to descriptions of minimum ICI in terminal buzzes of several odontocete species (Verboom and Kastelein 1997; Johnson et al. 2004; Koschinski et al. 2008; DeRuiter et al. 2009 Verfuss et al. 2009). All click trains with ICI <2 ms were manually inspected to confirm the presence of a buzz in the click sequence or they were discarded from the analysis. Click trains with ICI below 1 ms were omitted as multipath propagation of sound waves may result in double clicks due to different delays arriving at the T-POD along different paths, e.g., by reflexions from the water surface (Koschinski et al. 2008; Roy et al. 2010).

Potential differences between group sizes observed at day and night periods in Cape Beluzy were analyzed with one-way ANOVA, and results were compared to potential differences in echolocation activity.

Results

Experiments in captivity

Description of the echolocation click energy distribution

In order to obtain a representative sample of the echolocation click energy spectrum, 979 click trains were manually selected from a total of 9 h of recordings. Click trains included in the analysis were recorded at a variety of distances and angles from the animal beam axis, although many of these are assumed to be recorded on-axis while white whales were exploring the tubing that protected the hydrophone and cable.

The sound power spectrum composite showed a broad spread of energy from 40 kHz to 125 kHz (Fig. 2) with an average sound pressure level above background noise of 12.3 dB (4.3 SD). Peak sound pressure was 90 dB re 1 μPa centred at 73 kHz. A small peak observed at 148 kHz was an artefact of ineffective system grounding that was impossible to eliminate.

Evaluation of the performance of T-POD settings for white whale echolocation detection

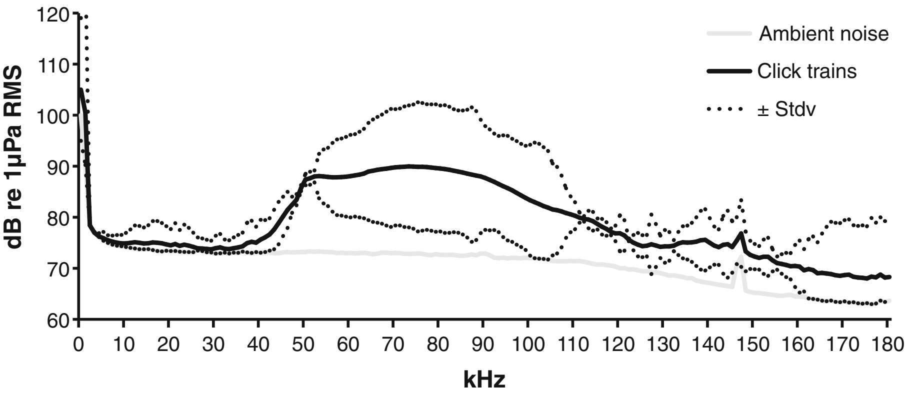
The T-POD was deployed at LOCAS 12 times in May 2006; in total 288 h and 5,935 echolocation clicks were logged. The frequency range 70/113 kHz (target/reference) was the best setting for the detection of echolocation signals from the captive white whales in both single and multiple frequency range deployment trials (Fig. 3). This range detected 66 % more DPMs than the poorest performance range (56/92 kHz). The range 50/30 kHz was second in order of performance for both trials. There were some discrepancies in detection results between the single and multiple frequency range trials for the ranges 92/130 and 70/92 kHz. However, these differences were small (in the order of 1.5 %).

Open water study areas

Validation of click spectra recorded in LOCAS

A group of approximately 40 white whales was encountered in Krossfjorden on 15 May 2007 and their echolocation clicks were recorded using an oscilloscope. A total of 127 clicks from 6 trains were recorded. Between 4 and 68 clicks were documented from each train. The actual trains produced by the white whales were undoubtedly longer, as the system was triggered by high sound pressure levels while a given animal was facing the hydrophone. The trigger level was gradually adjusted until a few trains were detected, as a means of obtaining only on-axis clicks from an animal facing the hydrophone. The captured sound samples showed clean train sequences. Most of the energy in the click trains was centred between 30 and 100 kHz, often with bimodal distribution and energy peak bandwidths

Fig. 2 Power spectra (dB re 1 μPa rms, and 1 × SD) from broadband recordings at 380 kHz sampling rate with a resolution of 1 kHz from 979 echolocation click trains on and off-axis from captive white whales (*black lines*) as well as ambient noise in LOCAS white whale facility (*grey line*)



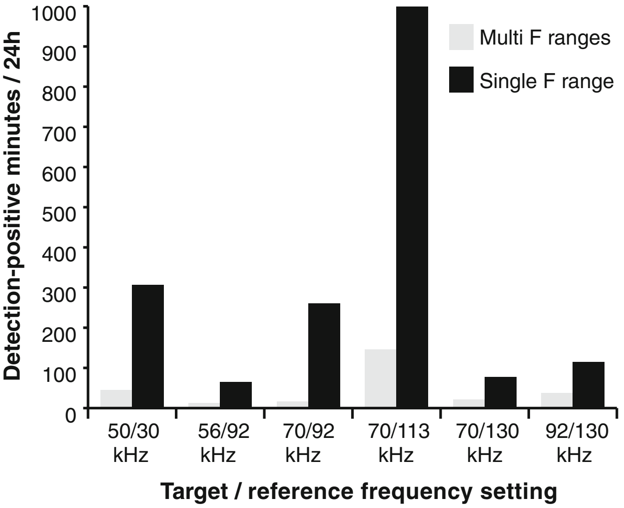


Fig. 3 Median number of detection-positive minutes for each frequency band scanned in 24-h deployments at the LOCAS white whale facilities. 'Single F range' refers to deployments in which the T-POD was set to a single frequency range and 'Multi F ranges' refers to deployments in which the T-POD was set to scan 6 different frequency ranges consecutively

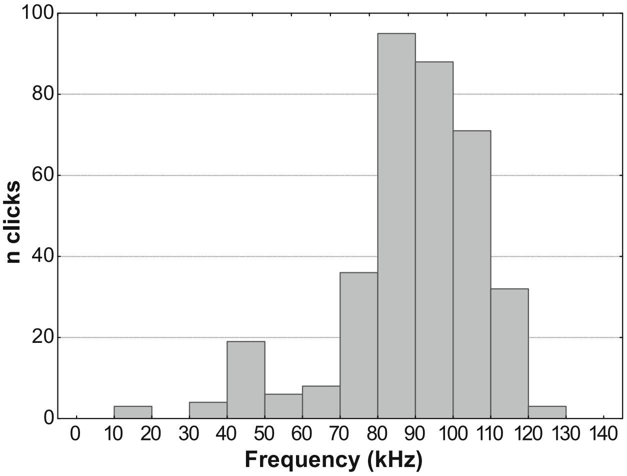


Fig. 4 Peak frequency of clicks as logged by a C-POD deployed in Disenchantment Bay, Yakutat, Alaska, May 2009

between 20 and 60 kHz. Because one of the two deployed C-PODs in Disenchantment Bay was never recovered, the sample size obtained was limited to 49 click trains with a total of 807 clicks. Peak frequency of the detected echolocation signals showed a bimodal distribution with a primary peak in the range 80–90 kHz and a secondary peak at 40–50 kHz (Fig. 4).

Deployment and collection of T-POD and C-POD data

Between 10 and 23 May 2007, T-PODs were deployed for 235 h in Kongfjorden. A total of 2,300 echolocation clicks were detected on 11 May in between 03:09 and 03:16 a.m. (local time) when no visual effort was undertaken. From all tested scanning settings (Table 1), 70/113 and 50/30 kHz (target/reference) were the two most successful at detecting click trains (55 and 22 % of total detected click trains, respectively). Krossfjorden sound recordings confirmed the absence of noise from ice-related sources in this study area.

Between 10 and 20 May 2008, four T-PODs were deployed for 607 h in Disenchantment Bay. A total of 167,579 echolocation clicks were detected throughout the deployment period. More click trains were detected by the 50/30 kHz (target/reference) setting (61 %) than the 70/113 kHz (39 %). Between 25 and 31 May 2009, a C-POD was deployed for 141 h in Disenchantment Bay. A total of 750 echolocation clicks were detected on May 28 and 57 echolocation clicks on May 30. Sound recordings made in the study area both in 2008 and 2009 revealed that ice movement and glacial calving created an extremely noisy environment. Broadband (full recording range 0–48 kHz) pulsive events of short duration (in the range of tenths of ms) and random occurrence were clearly related to the amount of ice surface coverage, particularly by growlers, and not by white whales. The acoustic characteristics of these pulses resembled echolocation clicks and thus were often logged by T-PODs and C-PODs. T-PODs logged 59,171,083 pulses of which only 167,579 (0.28 %) were classified as click trains with a high probability of being odontocete echolocation clicks ('Cet hi'). The C-POD logged 5,118,971 pulses of which only 807 (0.02 %) were classified as being cetacean echolocation click trains of high, moderate or low train quality ('Hi', 'Mo' and 'Lo').

Between 7 and 24 July 2008, one T-POD was deployed for 408 h in Cape Beluzy. A total of 1,612,091 echolocation clicks were detected throughout the deployment period. More click trains were detected by the 70/113 kHz (target/reference) setting (62 %) than the 50/30 kHz (38 %) setting.

Validation of T-POD and C-POD data: visual and acoustic comparison of white whale detections

In Kongfjorden, 44 of the 235 h of acoustic data collection included concurrent visual observations. White whales were sighted in the vicinity of the T-PODs on only two occasions. On 19 May 2007, a group of approximately four whales passed within 100 metres of the deployed units and were in the immediate area for about 1 h. On 21 May 2007, a small dispersed group of approximately eight whales passed the harbour over a period of about 20 min. No clicks were detected by T-PODs during either sighting, and no false DPMs were reported within the 44 h of visual effort. The only logged detections in this study area occurred when no visual effort was undertaken; therefore, these acoustic detections could not be validated.

In Disenchantment Bay, 61 of the 607 h of click data collected with T-PODs included concurrent visual observations. When these 61 h of data were initially processed using the 'Cet hi' level of classification and a click duration of at least 10 µs, no false DPMs were identified within the visual effort periods. All DPMs occurred during documented presence of white whales in the deployment sites. When the level of classification was lowered to 'Cet all' (including both 'Cet hi' and 'Cet lo'), the number of correct DPM increased but false DPMs were also identified (during periods of no sightings). False DPMs always corresponded to click trains of 'Cet lo' level. Therefore, 'Cet lo' detections were omitted in further analysis of this data set. A total of 37 of the 141 h of data collection with the C-POD included visual observations. When these 37 h of data were processed using the default train quality level ('Hi' and 'Mod'), no false DPMs were identified during concurrent visual observations, and all DPMs occurred when white whales were seen in the deployment site. When the train quality level 'Lo' was added to the data processing, all click trains included within this level fell within already identified correct DPMs containing 'Hi' or 'Med' level click trains and no false DPMs were observed. Therefore, detections with train quality levels 'Hi'. 'Mod' and 'Lo' were included in further C-POD data analysis.

In Cape Beluzy, 369 of the 408 h collected with the T-POD included concurrent visual observations. When these 369 h of data were processed using the 'Cet hi' level of classification, no false DPMs were identified within the visual effort periods. When the classification level was lowered to 'Cet all', correct DPMs increased but also false DPMs were identified. False DPMs always corresponded to click trains of 'Cet lo' level. Therefore, 'Cet lo' detections were omitted in further analysis of this data set.

White whale presence and diel patterns

Percentage of DPM per day at Disenchantment Bay deployment sites ranged between 8.3 and 79.2 %. The average number of DPM for each hour varied between 4.1 (1.8 SE) and 29.7 (14.6 SE) but no apparent diel patterns were found at any deployment site.

White whales were detected in Cape Beluzy every day of the 18 days deployment period. The percentage of DPM per day ranged between 41.7 and 75 %. The average number of DPM for each hour of the day ranged from 3.0 (11.8 SE) to 30.3 (4.5 SE). A significant diel pattern was found in echolocation activity ($F_{23,\ 237} = 1.58$, $p < 0.05$). Echolocation increased at dawn, peaked 3 h later and then gradually decreased through the day, with little signalling during dusk or night time (Fig. 5).

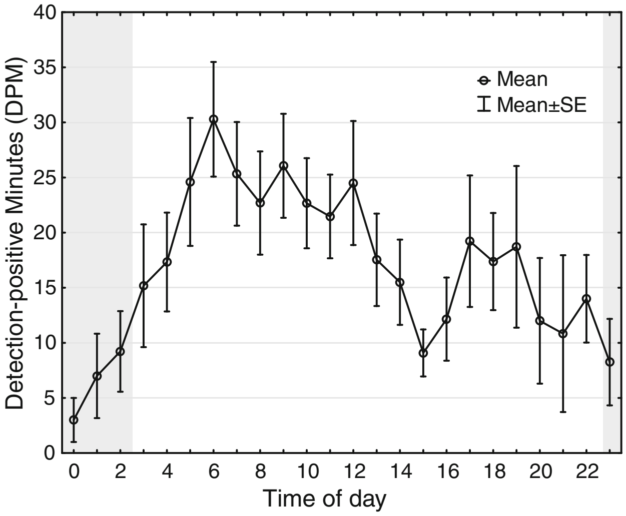


Fig. 5 Average number of detection-positive minutes (DPM ± SE) versus time of day in Cape Beluzy, Solovetskiy Island, White Sea, Russia. Data were pooled for each hour for all days. The *grey shadowed area* corresponds to the night time (from averaged sunset to sunrise of deployment period). Local time is GMT + 4 h

Movement patterns

Movement patterns from a total of 61 h of white whale visual observations in Disenchantment Bay were compared to the acoustic detection periods at each deployment site and the sequence in which those detections occurred. Only the comparison of 6 h 42 min of consecutive observations is described here as it is representative of the overall results. Criteria for selecting this period included the number of concurrent T-PODs deployed in the study area and the availability of continued focal animal sampling of white whales approaching and leaving the deployment sites. The selected period was 17 May 2008, when all four T-PODs were deployed, one near Haenke Stream site and three in a small bay between Haenke and Hubbard Glaciers, termed Beluga Bay (Fig. 1). The distance between Haenke Stream and Beluga Bay is approximately 1,400 m. Two observation teams concurrently covered the study area. Visual effort started at 8:30 (local time) and ended at 15:12. Figure 6 summarizes the detection sequences described below. A group of three sub-adult whales visited both deployment sites and travelled between sites several times during the observation period. The first sighting occurred at 12:20 when all three whales were sighted approaching Beluga Bay from the Haenke Stream site. The Haenke Stream T-POD detected click trains for a period of 7 min (until 12:03) from the focal group of whales moving towards Beluga Bay. The visual data log indicates that whales stayed at Beluga Bay from 12:20 until 12:42 when they moved back towards the Haenke Stream site. All three T-PODs in Beluga Bay detected clicks from 12:06 until 12:50 and the Haenke Stream T-POD started to detect clicks

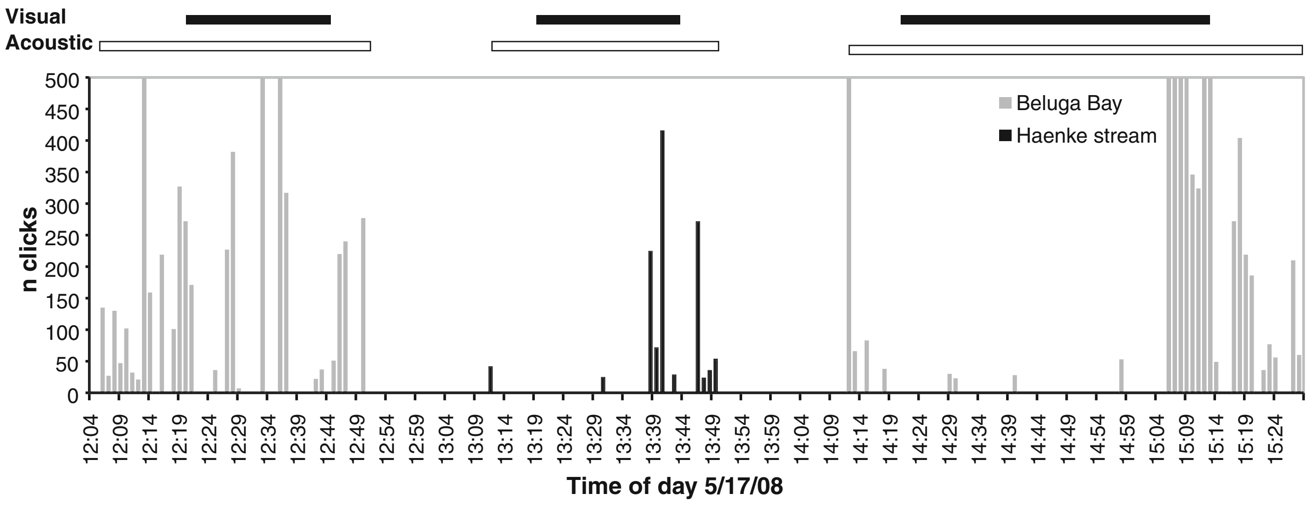


Fig. 6 Number of echolocation clicks detected for each location in Disenchantment Bay on 17 May. *Bars* across the *top* of the plot indicate visual (*solid*) versus acoustic (*open*) presence of white whales in Beluga Bay and Haenke Stream

at 13:11, 9 min before the first sighting at Haenke Stream. Whales were sighted again at 13:59 approaching Beluga Bay from Haenke Stream site. The Haenke Stream T-POD stopped logging clicks at 13:49. Whales were sighted in Beluga Bay at 14:19. Two of the three T-PODs at Beluga Bay started logging at 14:12, closely matching visual confirmation of the presence of the whales. The visual effort stopped at 15:12, when the whales were still in Beluga Bay. All three T-PODs logged clicks until 15:28.

Overall, the acoustic interpretation of the pattern and direction of movement between the Haenke Stream site and Beluga Bay area was easy to define and matched well with visual observation. On many occasions, such as in the example period described above, acoustic detections started several minutes before visual sightings and similarly, visual sightings ended minutes before acoustic detections terminated.

Relationship between tidal cycles and the presence of white whales

Yakutat Bay (lower Disenchantment Bay) tide levels were compared to logged T-POD angles in order to explore a possible relationship between these two variables. The angle data indicated that the study area did not show a slack tide period; the change in current direction from decreasing to increasing tide occurred quickly, and the largest angles (i.e. fastest currents) were logged before, during and after low tide level. This pattern was evident when drifting ice was present in the study area near low tide periods as drift directions shifted within seconds. (Figure ESM1 shows the relationship between tide level and T-POD angles in Beluga Bay for a period of 5 days). There is no tide table for the study area; therefore, tide data were obtained from Yakutat harbour tide table (35 nm south of the study area), but the tide conditions at the upper section of Disenchantment Bay, where the study site was located, are generally delayed by 10–13 min. Pearson correlation analysis between T-POD angle and echolocation activity was significant ($p < 0.05$) for all locations. The highest number of click detections for Beluga Bay locations occurred at low angles (i.e. slow currents at high tide); however, for the Haenke Stream location, the highest number of click detections occurred at higher angles (i.e. high currents near low tide) (Fig. ESM2).

A strong relationship (Pearson correlation analysis, $p < 0.05$) was also identified between T-POD angle and echolocation detection in Cape Beluzy, similar to the one observed in Haenke Stream deployment site in Disenchantment Bay. Whale detection consistently increased during higher angle periods (Fig. 7). Since the mooring design at this study area included a surface buoy, higher angles corresponded not only to faster flowing current periods but also to low tide levels, because when water depth was shallower the mooring line was loose, allowing the whole mooring system to remain tilted. Therefore, for this study area, white whale detection was most frequent during periods of high current flow and low tide. Visual data suggested that bigger groups of whales were generally observed at low tide levels, matching the increase in logged echolocation during higher T-POD angles.

Foraging behaviour

The percentage of buzzes in Disenchantment Bay ranged between 5 and 15.4 % of total detected click trains across deployment sites. Click trains were detected throughout the 24-h cycle in only two deployment locations (BB1 and BB3). A significant difference in minimum average ICI per

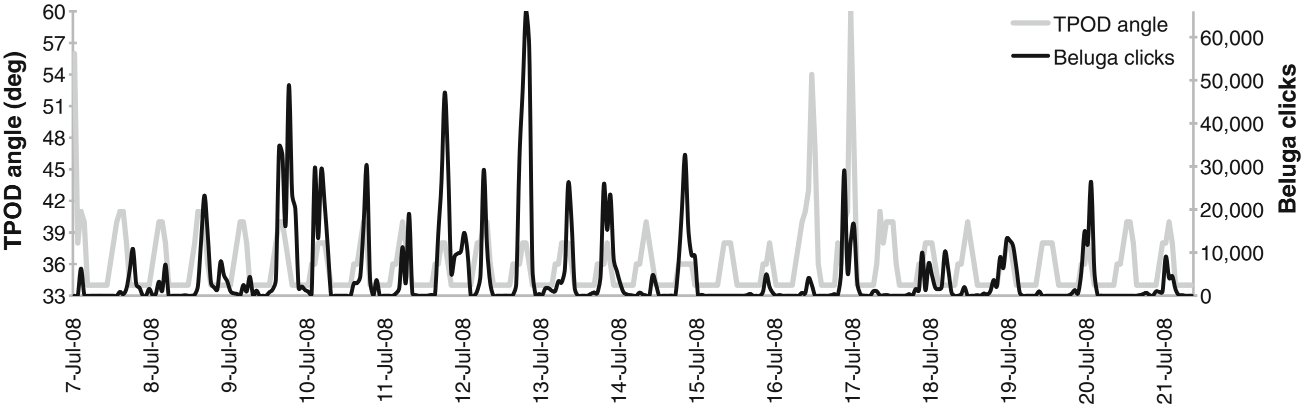


Fig. 7 T-POD angle versus detected clicks in Cape Beluzy, Solovetskiy Island, White Sea, Russia

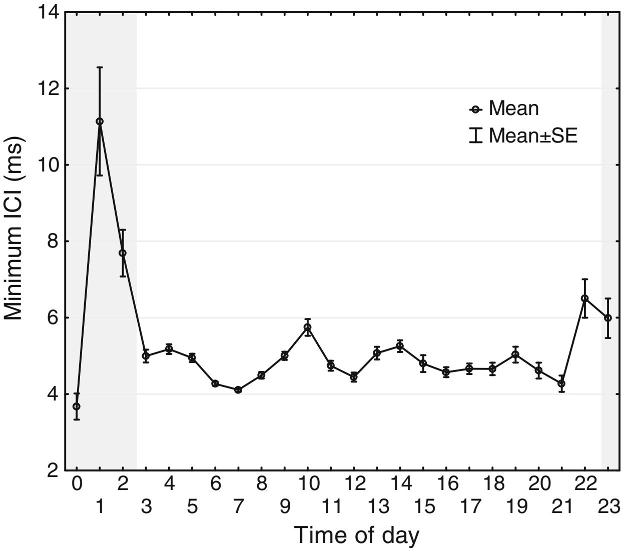


Fig. 8 Minimum ICI (mean ± SE) of each click train versus time of day at Cape Beluzy, Solovetskiy Island, White Sea, Russia. Data were pooled for each hour for all days. *Grey shadowed area* corresponds to the night time (from averaged sunset to sunrise of deployment period)

hour was found in these two locations ($F_{23,\ 744} = 1.96$, $p < 0.01$), ranging from 1.1 to 9.4 ms, but potential foraging behaviour did not show any clear diel pattern since buzzes were scattered throughout the 24-h cycle.

Only 2.9 % of all detected click trains in Cape Beluzy were identified as buzzes. Click trains were detected throughout the 24-h cycle. There was a marked diel pattern to ICI, with slower click trains occurring during the night period ($F_{23,\ 52099} = 17.85$, $p < 0.01$) (Fig. 8). Visual observations confirmed the continuous presence of white whales throughout the acoustic monitoring period (night time lasted an average of 3 h and twilight allowed visual monitoring through night hours). Group size varied from 3 to 40 whales with an average group size of 16 whales, but there was no evident diel pattern in group size ($F_{1,196} = 0.0034$, $p > 0.05$ for differences between group sizes observed at day and night periods) that could explain the observed diel variance in echolocation activity. However, surface behaviour observed during dusk and night time was predominantly resting behaviour which could be related to the slower clicking rate observed during the night period.

Discussion

Both T-PODs and the C-POD proved to be effective in detecting the presence of white whales both in captivity and in various arctic and subarctic environments. Comparison of visual detections of white whales and acoustic detection of their echolocation activity showed how these corresponded quite well, when data were processed at the high train quality level ‘Cet hi’ in T-POD data and when using ‘Hi’, ‘Mod’ and ‘Lo’ in C-POD data. These results suggest that both T-PODs and C-PODs are reliable instruments for white whale acoustic monitoring. When the train quality level was lowered to ‘Cet all’ in T-POD data, the number of correct DPMs considerably increased improving the match with visual data; however, false DPMs were also identified during periods when white whales were not observed. Thus, train quality level decisions are critical to obtaining a proper acoustic description of white whale presence. If limiting false detections is important in the study design, only the ‘Cet hi’ detection class should be incorporated in the analysis. It is interesting to note that all the false DPMs observed were attributed to the ‘Cet lo’ class, suggesting that if the ‘Cet all’ train quality level is used to improve the accuracy of acoustic encounters, those composed of exclusively of the ‘Cet lo’ class detections should not be considered as valid unless visually confirmed. This strategy would reduce the risk of accepting false detections while potentially increasing correct detections.

Results from Kongfjorden were in contrast to Disenchantment Bay and Cape Beluzy. This was the only study area in which T-POD data did not record click trains in the presence of white whales. Results from Kongfjorden suggest that the absence of acoustic detections do not necessarily reflect absence of white whales, at least in this study area. This matter was carefully analyzed in the T-POD data sets with concurrent visual observations from Disenchantment Bay and Cape Beluzy. In these two other study areas, white whales were never visually reported without concurrent T-POD detections at any of the deployment sites. Although this discrepancy could be related to differences in acoustic properties and hence detection ranges of the instruments, it is more likely related to differences in white whale acoustic behaviour. Water turbidity differences among study areas may explain, at least in part, potential differences in acoustic behaviour. Disenchantment Bay is a glacial and fluvial drainage basin, and thus, the waters are extremely turbid. Cape Beluzy is similar, located in the inner region of an inlet (White Sea) and influenced by the dynamism of the drainage basin of Onega River (Filatov et al. 2005). Kongfjorden on the other hand, had particularly clear water conditions at the time of the survey (Cottier et al. 2007) so white whales could rely on visual cues and reduce the use of echolocation for short range detection. Furthermore, it has been suggested that white whales may reduce their echolocation activity and vocalization rate as a mechanism to avoid predation (Morgan 1979; Lesage et al. 1999; Karlsen et al. 2002; Van Parijs et al. 2003); mammal-eating ecotype killer whales (*Orcinus orca*) are present in Svalbard (Øien 1988). In the Svalbard area, white whales are generally quiet and move rapidly in a directed manner in very shallow, coastal waters between foraging sites, which has been interpreted as predation avoidance behaviour (Lydersen et al. 2001). Therefore, echolocation monitoring may be most effective in turbid waters or in areas where killer whales are rare or absent.

Acoustic and visual comparison of data from Disenchantment Bay indicated that, in general, white whales were acoustically detected several minutes before being sighted and detections continued several minutes after the last sighting. As mentioned above, the turbidity of the water and heavy ice in Disenchantment made sighting white whales challenging. Nevertheless, movement patterns in and out of Beluga Bay were effectively tracked acoustically. These results suggest that acoustic effort is as effective as visual effort, or even more so, at least in the environmental conditions of this study area. However, acoustic results from Disenchantment Bay show that ice noise can overlap in frequency with white whale echolocation signals and this source of noise is extremely abundant, as noted by the very small percentage of echolocation logged within the millions of pulsive events detected by both types of loggers. Therefore, environments where there is a lot of floating ice will present challenges for detecting white whale via their echolocation signals. Carefully selected scanning settings, scheduled sampling strategies and click duration limits must be used for long deployments in this type of environment to minimize constraints due to memory shortage on the C-pods or T-pods. It is important to note that, even in such noisy environments, white whales were still successfully detected by both types of loggers and that presence and absence as well as movement patterns were successfully linked to visual observations.

Knowledge of the click energy spectrum was crucial to set T-PODs in a manner that maximized the chances for the detection of white whales. Scanning incorrect frequencies reduced the detectability of captive whales by one order of magnitude (see Fig. 3). There was a good correspondence in the range of maximum click energy obtained from off- and on-axis click train recordings in captivity (40–125 kHz, Fig. 2), peak frequencies from click trains recorded in Krossfjorden (32–90 kHz), and peak frequencies from click train detections reported by a C-POD in Disenchantment Bay (40–120 kHz, Fig. 4).

Au et al. (1985) described on-axis click peak frequencies for a captive white whale, suggesting that moderate to faint clicks had peak energy in the range 40–60 kHz and loud click energy peaked in the range 100–120 kHz. The bimodal peak frequency results from the C-POD deployed in Disenchantment Bay overlapped with the frequency ranges reported by Au et al. (1985), even though it is unlikely that all the clicks were logged on-axis, suggesting that the instrument was able to detect both echolocation modes and that echolocation clicks from captive white whales have similar energy content to signals from free-ranging white whales. These findings are based on a limited number of clicks, but if they are representative of white whales, they indicate that T-POD monitoring using default click-selection settings could, in the case of white whales, exclude many of their click trains. Including peak frequencies in the target frequency and low energy contents in the reference frequency (e.g. 70/113 and 50/30 kHz) proved to be the most efficient scanning setting. This highlights the importance of prior knowledge of the acoustic characteristics of echolocation signals from target species in determining the appropriate settings for monitoring.

Interestingly, the setting 70/113 kHz was more successful in both Disenchantment Bay and Cape Beluzy study areas and the setting 50/30 kHz was in Kongfjorden. This could be explained, in part, by the bimodal nature of their click energy content. An alternative explanation could be related to differences in background noise (e.g. ice noise) as it has been described that white whales are able to modify the energy content of their echolocation signals to accommodate for differences in background noise conditions (Au et al. 1985). Water turbidity could also play a role in the observed differences, since Kongfjorden was the only study area with clear waters. However, echolocation broadband recordings from all study areas would have been required to explore these hypotheses.

Mooring configurations in Disenchantment Bay and Cape Beluzy permitted the study of tide level and white whale presence in both Disenchantment Bay and Cape Beluzy. The presence of moderate tides seems to be an important ecological factor in both study areas (Chelton and Davis 1982; Berger and Naumov 2000). This environmental variable seemed to be an important white whale habitat preference driver. However, the relationship between tide level and white whale presence in Beluga Bay (Disenchantment Bay) was the inverse of that at Cape Beluzy. White whale echolocation signals were more frequent at high tide levels in all Beluga Bay deployment locations and at low tide levels in Cape Beluzy. These opposite results could be explained by the specific locations of the moorings, since results from the mooring placed outside Beluga Bay (Haenke Stream), in a deeper area, showed higher detections at low tides, similar to Cape Beluzy. These combined results suggest that white whales, at least in Disenchantment Bay and Cape Beluzy study areas, show a preference for shallow waters only during high tide periods.

Undoubtedly, changes in the vertical orientation of the T-POD cylindrical hydrophone will affect the detectability of echolocation signals. For this reason, a reduction of echolocation detection when the T-POD was tilted was expected; however, results from Cape Beluzy as well as from Haenke Stream site showed the opposite pattern, suggesting that the tilting effect in the detection of white whale echolocation was not strong enough to bias the detection results. Therefore, the idea of exploring the relationship between the tide cycle and the presence of white whales indirectly through the T-POD and C-POD angle seems promising.

In the case of Cape Beluzy, a strong diel pattern in echolocation activity was observed. Echolocation detections increased considerably at 02:00 local time, peaking at 07:00 and decreased steadily thereafter until reaching a low level at 23:00 (Fig. 5). This pattern matched the solar cycle: sunrise for Solovki region during the sample period was between 2:08 a.m. and 3:07 a.m. and sunset occurred between 22:19 and 23:15 (U.S. Naval Observatory 2012). The observed echolocation activity pattern could be explained by a daily movement in and out of the logger's range or by a change in echolocation behaviour throughout the day (Fig. 7). Visual observations support the latter suggestion, since white whales remained in the area during low-light periods. Interestingly, white whales also clicked at slower rates during low-light periods (see Fig. 8). Click rate started to increase at dusk and peaked 3–4 h later and then gradually decreased until a minimum was reached at dawn. Visual observations indicate that white whales predominantly milled or rested during low-light hours. In contrast, no diel pattern in click rate was observed in Disenchantment Bay where white whales were only intermittently present. Diel patterns in echolocation activity have only been reported for harbour porpoise, Risso's dolphins (*Grampus griseus*) and Heaviside's dolphins (*Cephalorhynchus heavisidii*). Faster click rates were found during the night time in porpoise echolocation data collected in Scottish waters, the North Sea and the Bay of Fundy, Canada (Carlström 2005; Todd et al. 2009; Haarr et al. 2009), in Risso's dolphins in the Southern California Bight (Soldevilla et al. 2010) and in Heaviside's dolphin data collected off Namibia (Leeney et al. 2011). But fast click rates also occurred during the day time in harbour porpoise data collected in the Bay of Fundy (Cox et al. 2004). It is still not clear whether these patterns are related to circadian rhythms, external cues (e.g. light/lunar cycles), diel activity of prey species or some combinations of these factors. The combination of changes in echolocation activity and click rate could potentially be used as an acoustic indicator of particular behaviours such as the observed reduction in echolocation detection and lower click rate during night time in Cape Beluzy when white whales primarily rest.

Data on ICI rates from Disenchantment Bay, in combination with behavioural observations, suggest that buzzes (minimum ICI <2 ms) might serve as an acoustic proxy for foraging behaviour. Most low ICIs were documented during periods of intense surface activity with synchronized diving, which is likely related to foraging. Furthermore, in Cape Beluzy, foraging behaviour was not apparent in the visual assessment of the whale's activities at the deployment site, and the proportion of click trains containing a buzz was low. Several studies have shown that, when odontocetes approach their prey, ICIs are reduced and the terminal part of their click trains is characterized by a sudden drop in ICI, which is referred to as a terminal buzz (e.g. Miller et al. 1995; Miller et al. 2004; Madsen et al. 2005; Johnson et al. 2008). Terminal buzz ICIs ranging from 1.5 to 10 ms have been described for several odontocete species (Johnson et al. 2004; Madsen et al. 2005; Koschinski et al. 2008; Verfuss et al. 2009; DeRuiter et al. 2009; Akamatsu et al. 2005, 2010). For the white whale, buzzes in free-ranging individuals have only been described by Roy et al. (2010). These authors speculated that click trains recorded during a short tracking period were related to foraging behaviour. Unfortunately, they did not provide any other evidence for foraging behaviour. The mean ICI of these buzzes was 6.9 ms, with minimum ICIs below 2 ms.

Results from the present study are in accordance with those of Roy et al. (2010) and suggest that the presence of buzzes (minimum ICI <2 ms) in white whale echolocation data could be related to foraging activity. White whales might use terminal buzzes as part of their echolocation behaviour while foraging. However, in the lack of evident foraging observations due to the low underwater visibility in our study areas, this hypothesis cannot be completely confirmed.

Conclusions

This study demonstrates the feasibility of monitoring white whales using echolocation loggers and describes some important features of the species ecology in three different environments, as examples of the potential application of this passive acoustic monitoring method in Arctic and subarctic regions. Echolocation loggers tested in this study proved effective for detecting the presence of white whales by their echolocation activity, even in challenging acoustic environments. White whale echolocation behaviour was variable between habitats. This might be related to habitat differences or the impact of differing risks of predation on acoustic behaviour. Thus, the effectiveness of passive acoustic monitoring will likely also vary by location. Diel and tidal behaviour patterns were identified. Echolocation loggers provide the opportunity to collect data on seasonal presence patterns, fine-scale habitat use, and behaviour, which are essential to effective white whale conservation management. Future monitoring efforts should consider the use of echolocation monitoring as a cost-effective means of collecting long-term data sets on this sentinel species in Arctic ecosystems.

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